ENHANCEMENTS TO BOUNDARY ELEMENT CATHODIC PROTECTION SIMULATION SOFTWARE

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Abstract

In recognition of the significance of corrosion in its various manifestations to the life-cycle costs of naval ships, the Dockyard Laboratory of Defence Research Establishment Atlantic has embarked upon a multiphase study related to the development of boundary element analysis methods to support cathodic protection system studies. CPBEM, a PC based software suite that models both sacrificial and impressed current cathodic protection systems for surface ships, was developed. Several enhancements were made to CPBEM in current work to address several shortcomings identified during the recent application of CPBEM to modern frigates. Enhancements were made to the graphical user interface making it compliant with the Windows style of user interaction. Modelling capabilities were extended, through the use of a new improved meshing algorithm based on the quadrilateral paving methodology, to include an ability to describe anodes in close proximity to one another, and to describe the transom stern of the ship. Provisions for multiple polarization curves and paint damage areas were made. Other enhancements included the ability to compute the electric potentials and electrostatic fields at user specified locations in the fluid. A Tecplot interface was also supplied.

Résumé

Étant donné l'impact des différentes manifestations de la corrosion sur les coûts globaux des navires de guerre, le Laboratoire du chantier naval du Centre de recherches pour la défense Atlantique a entrepris une étude en plusieurs phases visant la création de méthodes d'analyse par éléments de frontières, en appui aux études sur les systèmes de protection. Nous avons modifié le logiciel CPBEM, conçu pour les PC, qui modélise les systèmes de protection par courant imposé et par anodes sacrificielles. Afin de corriger certains problèmes révélés pendant la modélisation récente des frégates modernes, nous avons apporté diverses améliorations au logiciel. Nous avons modifié l'interface graphique originale pour la rendre conforme au style de l'interface Windows. Les capacités de modélisation ont été augmentées par l'ajout d'un nouvel algorithme de maillage, fondé sur une méthodologie de pavage quadrilatéral, ce qui permet de décrire les anodes proches les unes des autres et de représenter l'arrière en tableau du navire. Nous avons effectué des modifications pour tenir compte de plusieurs courbes de polarisation et de régions où la peinture est endommagée. En outre, il est maintenant possible de calculer les potentiels électriques et les champs électrostatiques dans l'eau à des points précisés par l'utilisateur. Une interface Tecplot a été installée.

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Executive summary

Cathodic protection is an electrochemical technique for preventing corrosion of a metal exposed to an electrolyte. The process involves application of DC electrical current to the metal surface from an external source. The external source can be either through a commercial power source (an impressed current system), or through connection to sacrificial anodes made of a metal with a large negative electrical potential, such as zinc, aluminum or magnesium (a sacrificial anode system). Effective application of cathodic protection can provide complete protection to any exposed areas for the life of the structure. The combination of an external coating and cathodic protection provides the most economical and effective strategy for the protection of ships.

In recognition of the significance of corrosion in its various manifestations to the life-cycle costs of naval ships, the Dockyard Laboratory of Defence Research Establishment Atlantic has embarked upon a multiphase study related to the development of boundary element analysis methods to support cathodic protection system studies. CPBEM, a PC based code that models both sacrificial and impressed current cathodic protection systems for surface ships, was produced. This code contains pre-processor for the generation of models, the main program, or solver, and post-processor for the viewing of results. Several enhancements were recently incorporated into the CPBEM code in the current contract. These enhancements include user interface upgrade, a new meshing algorithm, and pre-processor and post-processor improvements. The main goal of the enhancements was to improve efficiency in model generation, analysis and review of the output.

A true Windows-based graphic user interface (GUI) replaced the generic GUI used in the previous version. This upgrade makes CPBEM intuitive and easy to use for people accustomed to Windows style programs.

A more versatile algorithm replaced the previous meshing algorithm. This new algorithm, which is based on quadrilateral paving methodology, does not require any predefined arrangement of elements. It only needs a description of the boundaries (both exterior and interior) of the region to be meshed. The mesher automatically creates mesh-optimized elements based on the general mesh size and anode mesh size required by users.

Improvements to the pre-processor (model generator) included improved Windows style control dialogs (e.g. meshing control, anode controls), as well as new controls for the description of polarization curves and paint damage areas.

Wallace, J.C., Brennan, D. P., Chernuka, M.W., Wang, Y. 2002. Enhancements To Boundary Element Cathodic Protection Simulation Software. DRDC CR 2002-039. Defence R&D Canada – Atlantic.

Sommaire

La protection cathodique est une technique électrochimique permettant de prévenir la corrosion des surfaces métalliques exposées à un électrolyte. On applique à la surface du métal un courant continu produit d'une source externe. On peut soit utiliser le réseau de distribution électrique comme source de voltage (système par courant imposé) soit relier le bâtiment à des anodes consommables d'un métal dont le potentiel électrique négatif est très élevé, comme le zinc, l'aluminium ou le magnésium (système d'anodes sacrificielles). Utilisée correctement, la protection cathodique pourra, pendant la vie de la structure, donner une protection complète à toutes les surfaces exposées. L'utilisation combinée d'un revêtement extérieur et de la protection cathodique constitue la stratégie la plus économique et la plus efficace pour la protection des navires.

Étant donné l'impact des différentes manifestations de la corrosion sur les coûts globaux des navires de guerre, le Laboratoire du chantier naval du Centre de recherches pour la défense Atlantique a entrepris une étude en plusieurs phases visant la création de méthodes d'analyse par éléments de frontières, en appui aux études sur les systèmes de protection. Nous avons modifié le logiciel CPBEM, conçu pour les PC, qui modélise les systèmes de protection par courant imposé et par anodes sacrificielles. Ce logiciel comporte un préprocesseur qui génère les modèles, un programme principal (le solutionneur) et un postprocesseur pour l'affichage des résultats. Dans le cadre du présent contrat, nous avons apporté de nombreuses améliorations au logiciel CPBEM, notamment une meilleure interface utilisateur, un nouvel algorithme de maillage et des perfectionnements au préprocesseur et au postprocesseur. Nous avons procédé à ces améliorations pour accroître l'efficacité de la modélisation, de l'analyse et de l'affichage des résultats.

Pour rendre CPBEM plus convivial et plus facile à utiliser pour les personnes habituées à utiliser les programmes Windows, nous avons remplacé l'ancienne interface graphique générale par une véritable interface Windows.

Nous avons remplacé l'algorithme de maillage par un algorithme plus souple. Fondé sur une méthode de pavage quadrilatéral, cet algorithme n'oblige plus l'utilisateur à disposer les éléments d'une manière prédéfinie; seule une description des frontières intérieures et extérieures de la région à mailler est requise. L'algorithme crée automatiquement des éléments dont le maillage est optimisé, à partir des spécifications de l'utilisateur quant à la taille générale des mailles de la région et à la taille des mailles de l'anode.

Nous avons amélioré le préprocesseur (modélisateur) en ajoutant des commandes de style Windows (notamment le contrôle des mailles et le contrôle des anodes), ainsi que de nouvelles commandes permettant de décrire les courbes de polarisation et les régions où la peinture est endommagée.

Wallace, J. C., Brennan, D. P., Chernuka, M. W. et Wang, Y. 2002. *Perfectionnements au logiciel de simulation par éléments de frontière, de la protection cathodique.* DRDC CR 2002-039. R & D pour la défense Canada - Atlantique.

ABSTRACT

In recognition of the significance of corrosion in its various manifestations to the life-cycle costs of naval ships, the Dockyard Laboratory of Defence Research Establishment Atlantic has embarked upon a multiphase study related to the development of boundary element analysis methods to support cathodic protection system studies. CPBEM, a PC based software suite that models both sacrificial and impressed current cathodic protection systems for surface ships, was developed. Several enhancements were made to CPBEM in current work to address several shortcomings identified during the recent application of CPBEM to modern frigates. Enhancements were made to the graphical user interface making it compliant with the Windows style of user interaction. Modelling capabilities were extended, through the use of a new improved meshing algorithm based on the quadrilateral paving methodology, to include an ability to describe anodes in close proximity to one another, and to describe the transom stern of the ship. Provisions for multiple polarization curves and paint damage areas were made. Other enhancements included the ability to compute the electric potentials and electrostatic fields at user specified locations in the fluid. A Tecplot interface was also supplied.

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1. INTRODUCTION

1.1 Background

Cathodic protection is an electrochemical technique for preventing corrosion of a metal exposed to an electrolyte. The process involves application of DC electrical current to the metal surface from an external source. The external source can be either through a commercial power source (an impressed current system), or through connection to sacrificial anodes made of a metal with a large negative electrical potential, such as zinc, aluminum or magnesium (a sacrificial anode system). Effective application of cathodic protection can provide complete protection to any exposed areas for the life of the structure. The combination of an external coating and cathodic protection provides the most economical and effective strategy for the protection of ships.

In recognition of the significance of corrosion in its various manifestations to the life-cycle costs of naval ships, the Dockyard Laboratory of Defence Research Establishment Atlantic has embarked upon a multiphase study related to the development of boundary element analysis methods to support cathodic protection system studies. CPBEM, a PC based software suite that models both sacrificial and impressed current cathodic protection systems for surface ships, was produced (SSC File No. OSC93-00659-004 and SSC File No. HAL95-01149-104). This suite contains preprocessing and post-processing capabilities for the generation of models and the viewing of results. During the recent application of the software to the HFX platform, several shortcomings were identified that had be rectified in order to permit full use of the code in support of new research initiatives underway at the Dockyard Laboratory.

1.2 Summary of Current Work

This report describes work conducted to address recently identified shortcomings of the CPBEM software suite for the modeling of sacrificial and impressed current cathodic protection systems. This included upgrading the user interface. Previous versions of CPBEM could be easily transferred to and recompiled on a variety of computer platforms because of an avoidance of a dependence on a platform-specific GUI tools but its GUI lacked the elegance of those built on modern GUI tools. Consequently, its generic GUI was replaced with a true Windows-based GUI. This provided the added advantage that users who are familiar with Windows-based applications could use CPBEM without the need to for extensive training.

The previous meshing algorithm was also replaced with a more versatile algorithm that does not produce only predefined arrangements of elements. This new algorithm only needs a description of the boundaries (both exterior and interior) of the region to be meshed. The mesher automatically creates shape-optimized elements. In addition, the new mesher also meshes the transom stern region, which was previously omitted from CPBEM meshes.

Further improvements to the preprocessor (mesh generator) included improved Windows style control dialogs, as well as new controls for the description of polarization curves and paint damage areas.

The CPBEM solver was also improved. The improvements included the upgrading to an iterative solver algorithm, the provision of the option for modelling multiple cathodic and anodic regions using one or more polarization curves, and the provision of a capability for computing the electric potentials and electrostatic fields at user specified locations in the fluid.

Finally, appropriate upgrades of the post-processing and visualization capabilties also formed part of the work. This involved two approaches. Within CPBEM, a capability based on modern GUI tools was provided. Also, a CPBEM to Tecplot interface was supplied so that both surface electric potentials and field potential values could be plotted.

2. PROGRAM USER INTERFACE UPGRADE

CPBEM was originally developed to be independent of any specific computer platform graphical-user-interface (GUI) tools, such as Windows. Consequently, CPBEM could operate on a variety of computer platforms. With the widespread use of PC's with the Windows operating system came a demand for programs to incorporate a Windows style GUI. Making CPBEM intuitive and easy to use for people accustomed to Windows style programs required the replacement of the previous CPBEM user interface with a completely new GUI. This change affected all aspects of a CPBEM analysis, including model generation, analysis and post-processing which were previously handled by three separate programs.

Model generation in CPBEM involves user interaction for input of modeling parameters, generating a mesh based on user input and displaying the mesh. In the previous version of CPBEM all three aspects of model generation were integrated into a single FORTRAN program. One of the most important aspects of the present work included the separation of the user input and viewing function from the mesh generation function. All user interactions and viewing procedures would then be handled by the new Windows-based driver program while the mesh generation procedures would continue to be achieved with the original FORTRAN program code. This organization would require a means of linking the driver with the FORTRAN code.

Similarly, use of a Windows-based driver (effectively written in C++) allowed the FORTRAN-based analysis software modules to be incorporated into the new driver.

Post-processing CPBEM results had been handled by a third program in the CPBEM suite. This was another FORTRAN program that was not Windows-based. Two approaches were offered. The first involved presentation of CPBEM using the Open-GL based graphics inherent to the visualizations already provided within the new Windows version of CPBEM. The second approach involved provision of an translator capability that would produce results in the format required by Tecplot which is a very powerful, independent Windows-based plotting program.

2.1 Program Development Environment

In order to expedite this work, the plan was to make use of an existing Windows-based driver program developed at Martec for other DREA applications. This driver program was developed using the Microsoft Visual Development Studio, OpenGL and the C++ programming language. Program design was based on the standard document/view approach in which data and control over the presentation of that data was separated into separate classes. A strict hierarchy of data and view classes had been already developed for this driver. All viewable objects were added to a "scene graph" which made use of a considerable amount of base functionality especially in managing the view and manipulating object data.

A copy of the new driver was inserted into a new Visual Development project (a Microsoft program development environment for Windows program development). This "project" served as the development environment for the new CPBEM driver program that would include both model generation and analysis.

This new driver contained many classes and features that could be utilized by CPBEM. There were classes for hull forms, lines-of-form, anodic panels, cathodic panels, insulated panels, and polarization curves. For each of these, there was a class that would provide a user-interface. Also, there were capabilities to graphically display all but the polarization curve class, to analyze a cathodic protection system model, and to display analytical results.

2.2 Geometric and BE Model Objects

After reviewing the organization of the new CPBEM driver, it was determined that the data objects needed for CPBEM would include:

- a *hull form* object that would include several higher level data objects which describe specific details a hull model,
- several *line of form* objects that describe the profile of the hull at specific stations, and each in turn, is made up of offset objects,
- a *bow-line* object that provides a description of the bow profile,
- numerous *offset* objects that specify the location of points on a line of form,
- multiple *anode* objects that describe anode locations, inputs and sizes,
- a *shaft* object that describes the point where the external shaft penetrates the hull,
- a *rudder* object that describes the rudder connection point on the hull,
- multiple *damage area* objects that describe sections of the hull that have paint damage, and
- multiple *polarization curve* objects that describe the needed polarization curves.

These objects were organized as shown below in Figure 2.1.

For each new object type (hull form, line of form, anode, etc.) the tasks of data manipulation and data specification were separated into two classes. One class handled how data was used within the CPBEM model description and how the different pieces of data interrelate. The other class handled how the data was displayed and how the user accesses and edits the data. In the case of line-of-form data, the CLineOfForm class contains the line-of-form data, including the individual offset objects that make up the line-of-form, while the ClineOfFormPage class contains the functionality to display the data, as shown in Figure 2.2. This approach to object design follows the View/Document approach to GUI development commonly used today.

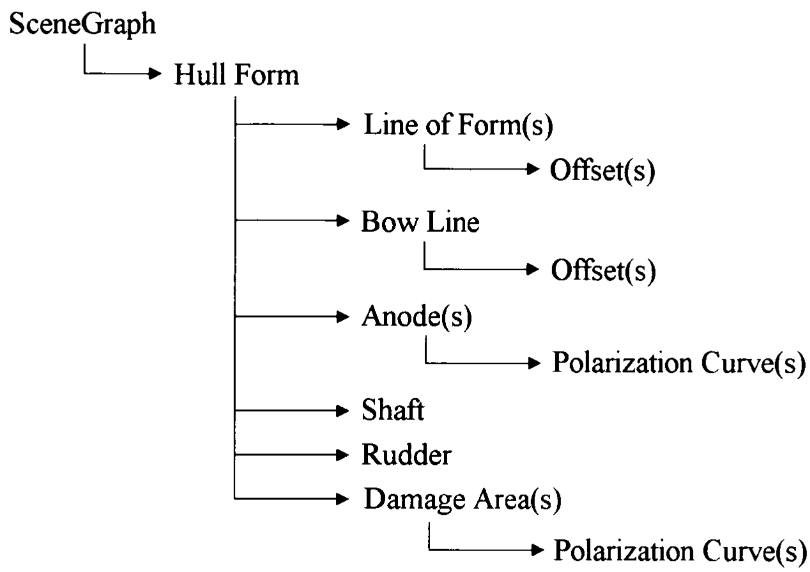

Figure 2.1 CPBEM Data Objects

Much of the base functionality required for each CPBEM object is contained in existing base classes previously developed as integral parts of the driver program. In the case of the lines-of-form, the following classes are used:

• **ClineOfForm**	which handles the actual data parameters and the ability to graphically display the data,	inherits from **CavastParent**	which handles lists, such as lists of offsets.
• **ClineOfFormPage**	which handles user-interaction for the lines-of-form,	inherits from **CavastPropertyPage**	which automatically handles user interactions for parent class data.

While the driver program contains a simple geometric description of the hull (a collection of lines-of-form), the tasks of creating a geometric "surface" from the input data and meshing that surface was left to the Fortran code used in the previous version of CPBEM. An executable program was created from the Fortran code, devoid of any direct user interaction.

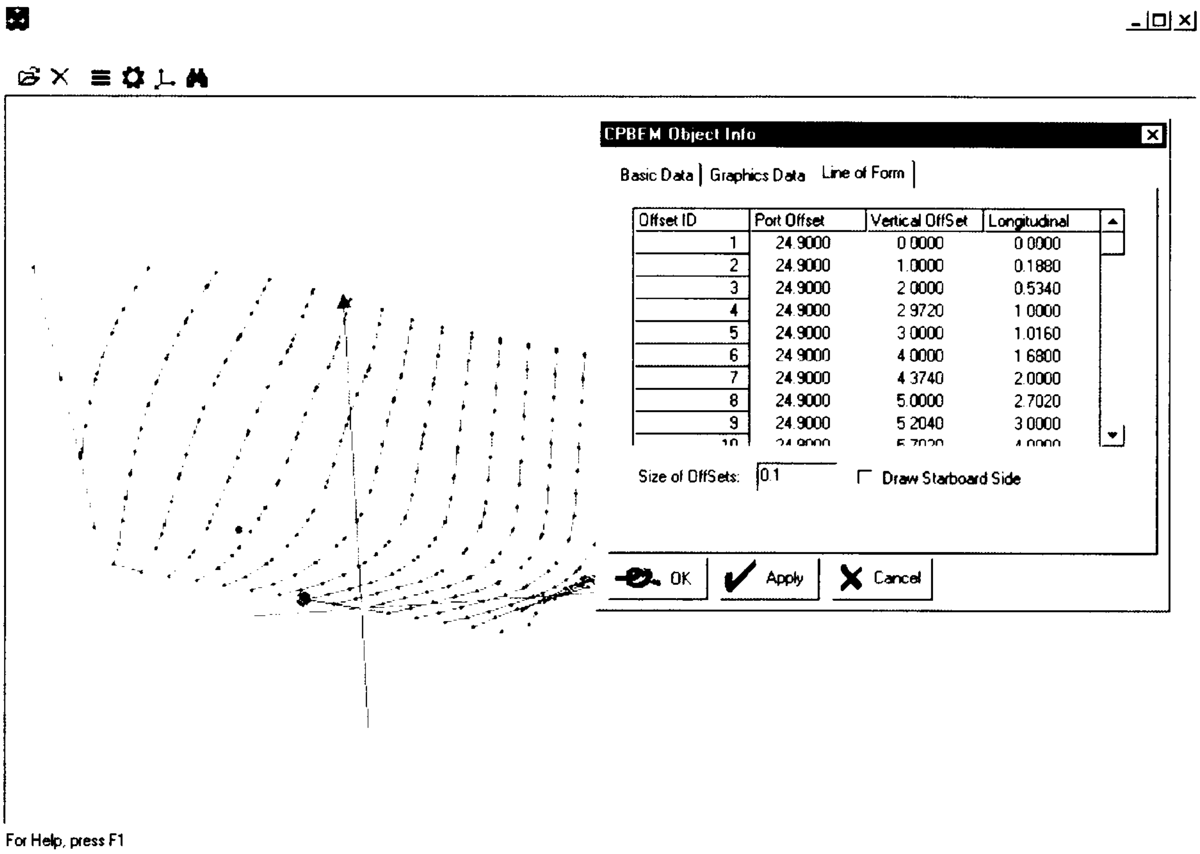

Figure 2.2 CPBEM screen shot showing "Line of Form" dialog

2.3 Mixed Language Interaction

All user interaction in the original Fortran meshing program had to be deactivated and replaced with the capability to read all data and command instructions from an ASCII input file, and to store all mesh data in an ASCII output file. Data transfer was via these input/output files. Interfacing the two programs was accomplished by creating, within the driver program, the capability to execute the Fortran program in a separate process and wait for it to terminate before resuming execution.

While not the most computationally efficient means of linking programs, this approach was the most expedient. Performance is acceptable, particularly after the addition of a new spline curve class to the driver program, as described in section 3.1 of this report.

2.4 Controls and Dialogs

As stated previously, the driver program already contained many of the needed features required by CPBEM. This included dialogs for user interaction. Existing user-interaction dialogs for lines-of-form and other objects provided a template for new objects , such as bow lines and damage areas. As illustrated in section 2.2, each dialog class makes use of the base class CavastPropertyPage in order to manage the “Basic Data” and “Graphics Data” tabs that appear along side the “Line of Form” tab in Figure 2.2.

3. PAVING MESHER IMPLEMENTATION

Another important upgrade involved replacing the previous meshing algorithm in CPBEM with a more versatile paving algorithm. Pavers do not require a pre-defined arrangement of elements, instead they take a description of the boundaries for a closed planar region (including nodal locations along the boundaries) and produce an irregular arrangement of elements within that region, as shown in Figure 3.1. Typically, element shapes are automatically optimized. Another automated feature with pavers is the automatic grading of element sizes between high and low density meshes. An existing paving mesher was used in the new version of CPBEM. Requirements for this mesher included:

- a planar surface,
- an even number of element divisions along each boundary,
- coordinates of all node locations on the exterior boundary,
- coordinates of all nodes on interior boundaries (cut outs).

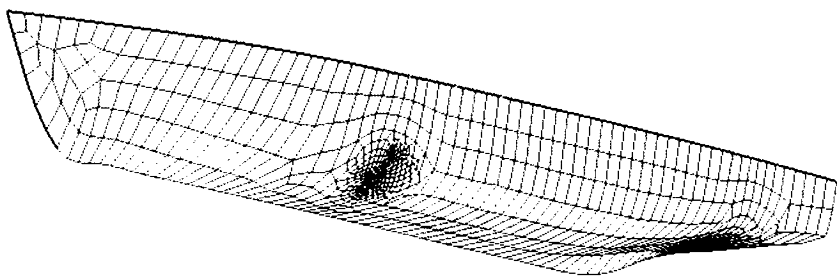

Figure 3.1 Sample Paver Mesh

3.1 Data Transfer

The modelling and meshing algorithms in the Fortran program required, as input, the lines-of-form that describe the portion of the hull to be meshed. Lines-of-form are therefore also part of the input for the driver program, although these lines describe the entire hull, while only the portion below the waterline gets meshed. Hence, it was necessary to clip the lines-of-form immediately prior to passing them to the meshing program. An existing algorithm in the driver provided this capability, but it was very slow. This lack of speed, when coupled with the time required to mesh the hull, meant that a user had to wait for an appreciable period of time after requesting a mesh and before user control would return. Consequently, a new spline curve class that would better handle the task of clipping the lines-of-form was added to the driver program. This new class reduced the time needed to clip the lines-of-form to a fraction of a second.

All meshing parameter values also had to be passed to the Fortran program. Polarization curve data was also passed, even though it is not strictly needed by the meshing algorithms. Its inclusion simply ensured that the anodic and cathodic element data returned to the driver program would be complete and hence would not require any subsequent processing or manipulation.

3.2 Mapping to Planar Meshing Surface

The most challenging requirement of the mesher was that it operated on a planar surface. No doubly curved surface can be flattened without introducing some topographic distortions. The challenge, therefore, was how to flatten the hull surface such that distortions were minimized. Since a ship hull is primarily curved in one direction, along the lines-of-form, it was concluded that a shell expansion that straightened each line-of-form and placed each straightened line on the ship center-plane would be a suitable approach. The resulting planar surface preserves the general shape of the hull reasonably well, including its aspect ratio and angles between boundary segments, as illustrated in Figure 3.2 (denoted as the "shell expansion" view). As a result, the process of mapping elements created on the flattened surface back onto the actual hull surface should preserve the high quality element shapes produced by the paver.

This approach requires a multiple phase-mapping procedure. The parametric mappings used in CPBEM to describe the hull geometry make it necessary to break the hull into one large four sided region that goes from the forward-most line-of-form to the stern, and a smaller region that extends from the forward-most line to the bow. Each of these two regions is modelled in parametric model by a square of unit size. Since the flattened hull does not fit this description, the process of mapping from the flattened space to 3D space required two steps. In the first step, any location on the flattened surface is converted to parametric coordinates by calculating the longitudinal and vertical positions as fractions of the entire surface length and arc-length (at that longitudinal location), as illustrated in Figure 3.2. In the second step these, normalized coordinates are fed into the parametric mapping functions thereby producing the 3D location of the point of interest.

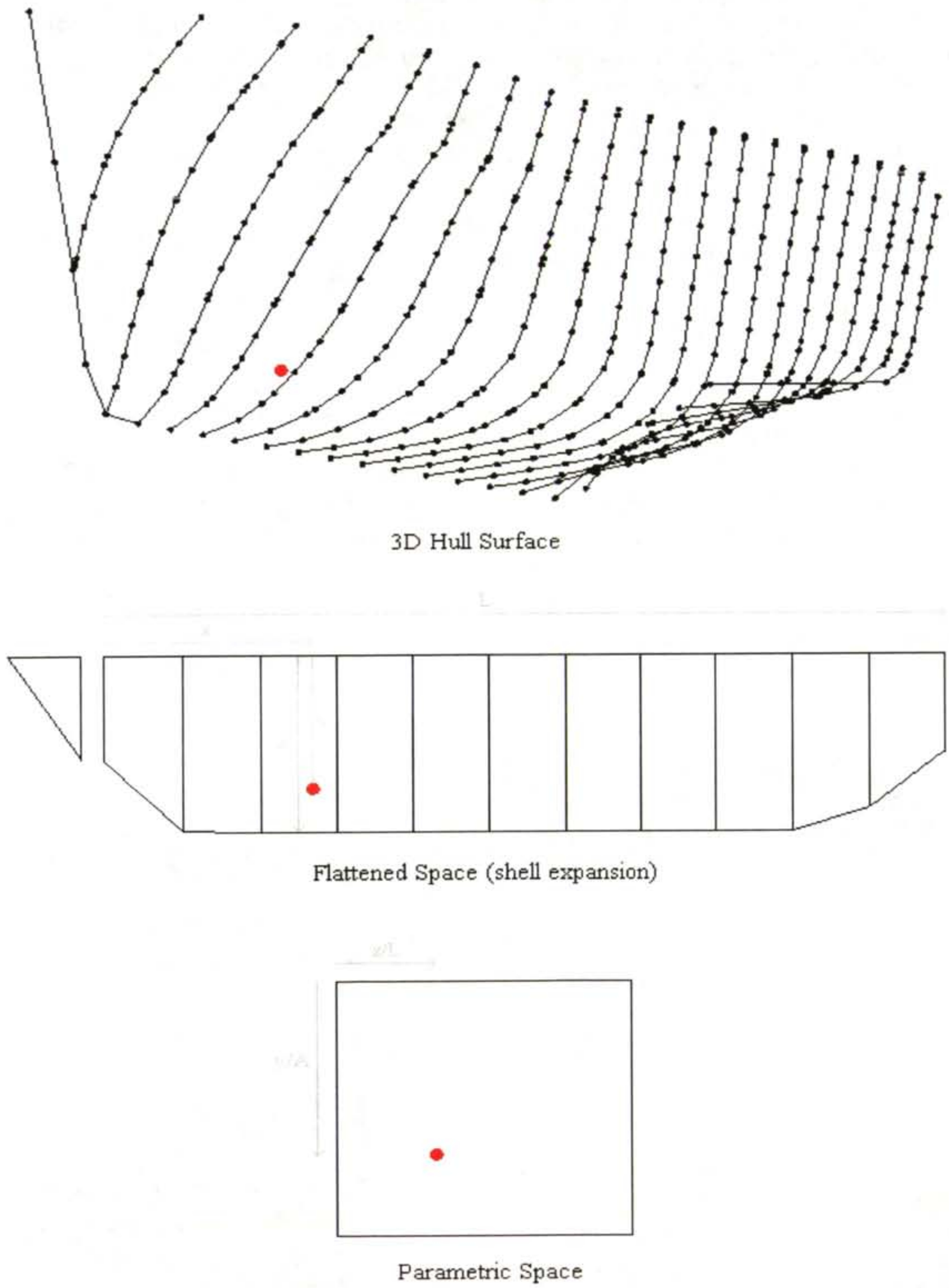

Figure 3.2 Hull surface in 3D space, flattened space and parametric space

Geometric descriptions of the four-sided hull patch in planar and 3D space make use of a spline surface, which is capable of describing a smooth (C^2) surface. It is through the use of this spline surface that it is possible to describe the complex 4-sided hull surface as a single geometric patch. The three-sided patch is described with a simpler cubic surface that uses linear interpolation along two of the three sides.

The shell expansion and two-step mapping algorithms were converted into computer code and incorporated into the Fortran program.

3.3 Transom Stern Mesh

In the past, CPBEM models typically only described wetted hulls that did not include the stern area. Hence, there was no need to include the ability to mesh the stern. In the interest of generality, there is now an interest to model the CPF with a waterline that significantly encroaches on the transom stern. Consequently, the Fortran program was enhanced through the provision of an algorithm to create a separate meshable region for the wetted region of the transom stern. This was a three-sided region bounded by the aft-most line-of-form, the waterline and the plane of symmetry. The mesh for this region was merged with the other meshed regions before storing the final mesh data set in the output file.

Since the user may specify a waterline that was only slightly above the bottom of the stern, as illustrated in Figure 3.3, consideration had to be given to what to do with a very narrow stern region. The boundary element solver used in CPBEM expects elements to have an aspect ratio of no more than 7-to-1. Hence, an aspect ratio check was included. If the estimated ratio was greater than 7, the aft-most line-of-form would be altered by pushing all control points up to the waterline, thereby eliminating the stern region altogether.

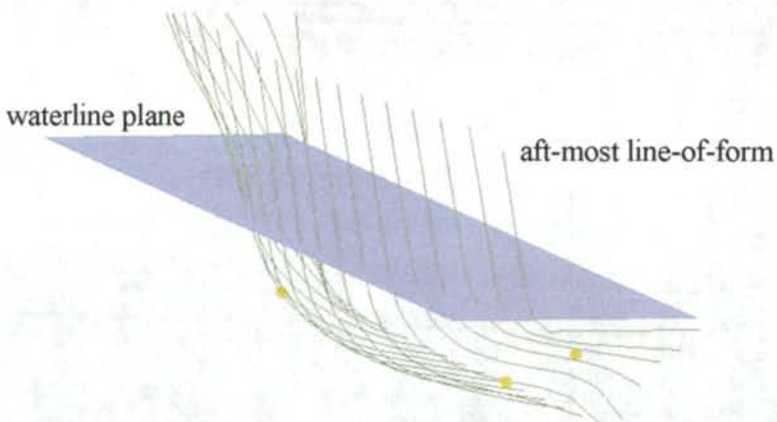

Figure 3.3 Transom Stern Geometry

If the resulting distortion is unacceptable to a user, a finer mesh should be requested and elements with smaller aspect ratio produced, and thereby forcing the program to include the stern region. Of course, this is done at the cost of an otherwise unnecessarily large number of panels.

3.4 Creation of Hull Boundary Descriptions

Since the paver does not provide any user control over the arrangement of elements in the interior of a region, it was necessary to mesh the anodes (which are of a prescribed shape and size) separately. This was possible because the paver that was incorporated into CPBEM is capable of meshing a region with interior boundaries (cutouts). Figure 3.4 shows a close-up of the aft portion of a hull, looking from underneath. In this figure, the outer edge of the symmetric hull model is shown. This makes up the exterior boundary of the hull region. Also shown in the figure is an anode, which defines both an interior boundary for the hull region and an exterior boundary for the anode region.

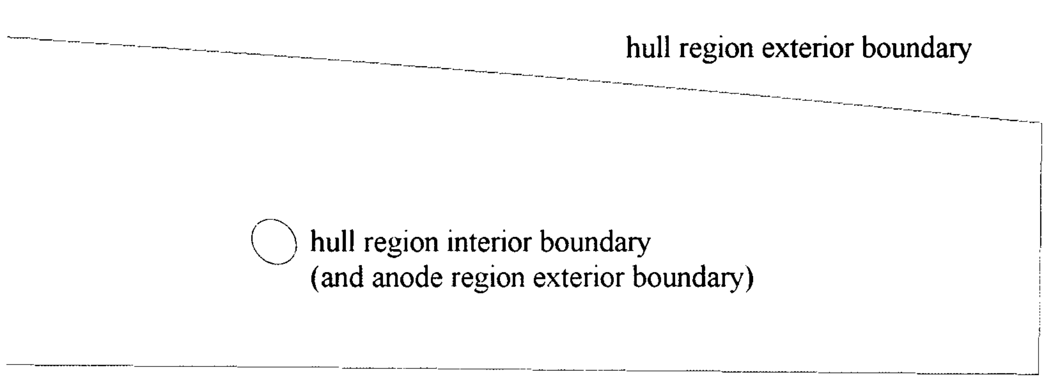

Figure 3.4 Mesh Boundaries

The paver requires the location of all penetrations and their shapes. Consequently, it was necessary to calculate each node location on the perimeter of the hull surface, as well as along the perimeter of the shaft penetration and each of the anodes. Node spacing along the hull perimeter was based on the user-specified default mesh size, as well as the proximity of the anodes and shaft penetration point. Since the paver has difficulty producing a mesh when size gradients (the ratio of adjacent element sizes) approach or exceed a value of 1.4, it was necessary to adjust node spacings along the outer boundary whenever gradients approached or exceeded 1.4. In order to be safe, a maximum allowable gradient of 1.2 was imposed.

Typically, anode and shaft mesh sizes will be considerably smaller than the default mesh size. Hence, if an anode or shaft penetration point lies in close proximity to the outer hull boundary, node spacings along the exterior boundary will have to be graded from the default mesh size to a smaller size. This smaller size will be dependent on the anode mesh size and the proximity of the anode to the exterior boundary. Figure 3.5 shows and anode in relatively close proximity to the exterior boundary. The circle defines the limit of the graded node spacings. All portions of the exterior boundary inside this circle will require graded node spacings, while portions outside the circle can use the default mesh size for all node spacings.

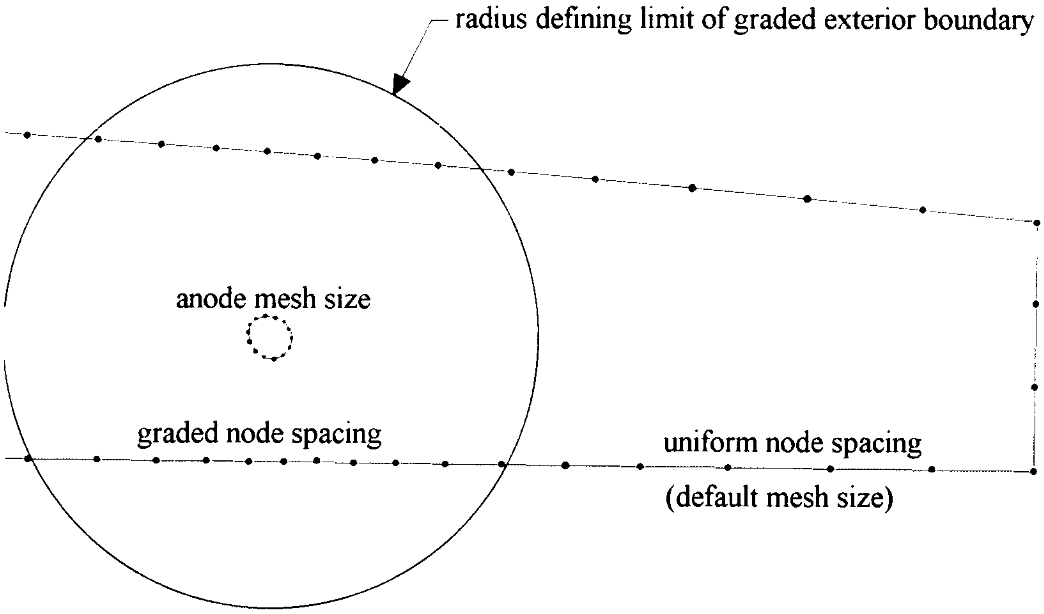

Figure 3.5 Node Spacings on Exterior Boundary

Node spacing along the perimeter of each anode was simply based on the user-specified anode mesh size. When it came to the shaft penetration, node spacing was based on the expectation that, in the shaft mesh file, there should be 20 elements at the end of the shaft.

An additional consideration when generating boundary descriptions was the paver requirement that the total number of divisions along a continuous boundary most be even. This requirement arises directly from the fact that the paver uses only quadrilateral elements.

3.5 Element Conversion

There are three different types of CPBEM elements (or panels). Anodic and cathodic panels are used to model anodes and cathodes, respectively, while insulated panels are used to describe all other parts of the hull surface (when there is no paint damage or deterioration). The paver does not distinguish between these element types. Hence, the task of specifying element types had to be separate from the task of meshing.

In the case of anodes, these were already being meshed as separate regions. It was only necessary to attach the required additional data (polarization curve or current density value) to the panels generated by the paver.

Cathodes were also easily created since they are stored in pre-meshed files, complete with all necessary polarization curve data.

Damage areas could be either anodic or cathodic. These were dealt with by identifying hull surface panels (in flattened space) whose centroids lie within a damage area. Again, the appropriate data was then attached to the identified panels.

4. PREPROCESSOR IMPROVEMENTS

4.1 Meshing Controls

User control over meshing is limited. As shown in Figure 4.1, there are only three meshing parameters that the user is able to modify. The "default mesh size" and the "anode mesh size" parmeters control mesh sizes along exterior and interior hull boundaries respectively. These boundaries are described in detail in section 3.4. The "Beasy file creation" parameter is a flag that controls whether or not a BEASY input file is to be generated. When activated, this flag causes CPBEM to convert the boundary element model to BEASY format and store the converted data on file.

While CPBEM allows for the propeller and rudder structures to be included in the modeling, it is assumed that they have been meshed independently of CPBEM and provided in separate files in standard VAST geometry file format to define nodes and elements associated with the surfaces of these structures (internal structure is ignored). The element type assumed to be contained within these files is defined as the VAST element type number. Controls are provided for the identification of the names of the propeller mesh file and rudder mesh file being provided. If the propeller mesh includes a shaft, then CPBEM incorporates the propeller mesh into the overall model by including an additional interior boundary in the hull boundary description, as described in section 3.4 of this report. By contrast, the rudder mesh is not modeled with an explicit structural connection with the hull mesh although a connection is implied by the analysis.

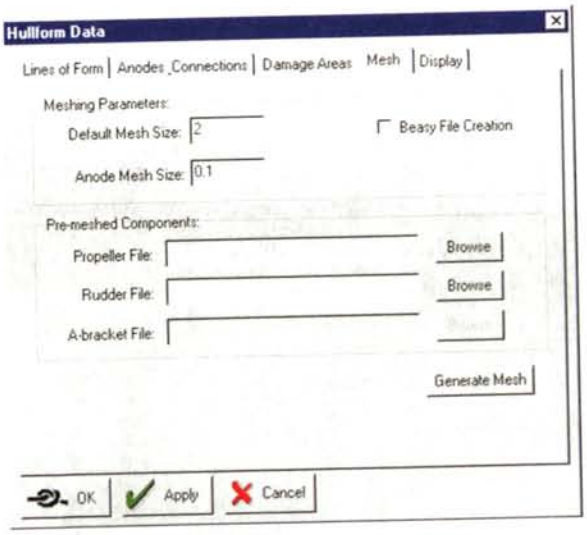

Figure 4.1 Mesh Dialog

4.2 Anode Controls

Anode controls were expanded from the original form in which anode location and input current were specified to also permit user control over anode size, type (impressed current or sacrificial anode) and polarization curve (for sacrificial anode systems). Figure 4.1 shows the anode dialog box. This same information is also displayed in the "Anode and Shaft Locations" tab in the hull form dialog box.

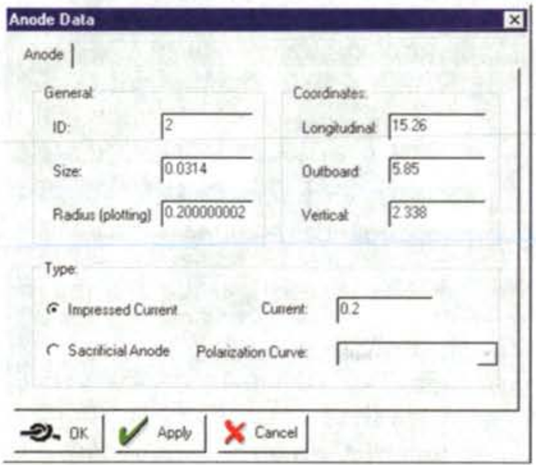

Figure 4.1 Anode Dialog

Previously, anode size was controlled by the size of the single anode panel at the anode location. The anode current density was adjusted to achieve the specified input current. This meant that while the resulting current density value at the anode was not correct, the total input current was correct. The only manifestation of this approach was a very localized inaccuracy in the current density contours. Studies showed that this error quickly died away as distance from the anode increased. Nonetheless, by including anode size in the anode user controls, it became possible to assign the correct area to each anode. As a consequence of providing user-control over anode size and anode mesh size, each anode region could be populated by more than a single element. The shape of each anode region was assumed to be circular, or as close to circular as is possible by a collection of first-order (straight-sided) elements. Creating the anode region boundary required the creation of an n-sided polygon which had the specified area. Equation 4.1 was used to determine the number of sides.

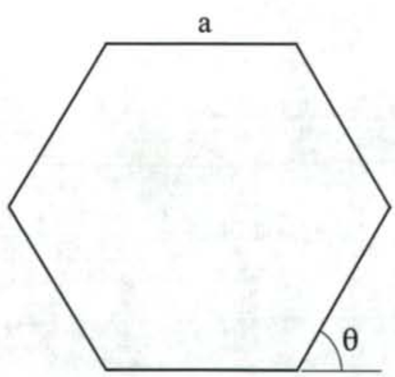

Figure 4.2 Anode Shape

$$n = \frac{(1-\cos\theta)}{\sin\theta} \cdot ratio^2 \qquad where \quad ratio = \frac{2 \cdot \sqrt{area}}{a} \quad , \quad \theta = \frac{2 \cdot \pi}{n} \tag{4.1}$$

Linear regression was used to produce a linear function for the number of polygon sides, that approximates Equation 4.1 extremely well (coefficient of determination=0.9997) as follows.

$$n = 1.7657352 \cdot ratio + 0.46852964 \tag{4.2}$$

The anode type control was designed to activate either the user-control for input current or the user control for polarization curve selection, depending on the type of anode selected. For sacrificial anode systems, only polarization curves with anodic data are displayed. Upon clicking the "OK" or "Apply" button, all of the specified data would then assigned to the anode object.

4.3 Paint Damage Definition

In previous versions of CPBEM, the entire hull surface, excluding anodes and cathodes, was assumed to be perfectly insulated; that is, it was assumed that there was no paint damage on any part of the hull. Of course, paint damage does occur as a result of contact with foreign bodies in the fluid and this can affect the behaviour of cathodic protection systems. Damage areas will behave as either cathodes or anodes, depending on the potential in that area. Unfortunately, potential values for each damage area element are known for certain only after an analysis.

Allowing for paint damage definitions within CPBEM required adding the ability to define damage areas and adding the ability to account for them in the analysis. In order to define a damage area, a new damage area dialog, as shown in Figure 4.3, was provided in CPBEM. Included in this dialog are controls to add or delete areas, specify type (anodic or cathodic), to select an appropriate polarization curve, and to start/stop the process of defining the damage area by selecting points along the area boundary. Considerable care must be taken when assigning a type to each damage area.

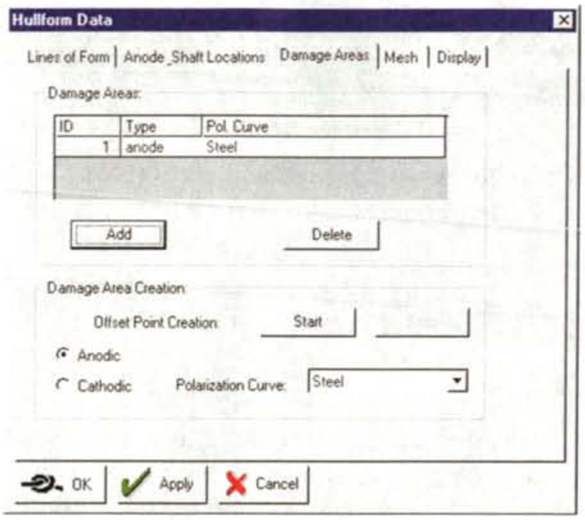

Figure 4.3 Damage Area Dialog

Accounting for damage areas within an analysis is done by assigning the specified type to elements inside each damage area. As described in section 3.3, the process of assigning the specified element type data to the damage area elements occurs following the generation of the hull mesh. Any element with a centroid inside a damage area is assigned the properties of that area. Figure 4.4 shows an example of a specified damage area and the resulting mesh. In this example, all panels with centroids inside the four-sided damage area have been made anodic. For clarity, these panels have been shaded.

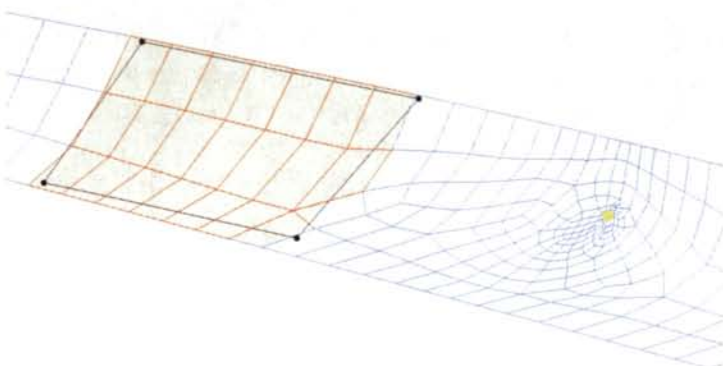

Figure 4.4 Damage Area Mesh

4.4 Polarization Curves

Previously there was no user control over polarization curve parameter values assigned to anodes and cathodes in CPBEM. Of course, this was a limitation that needed to be addressed. The new driver program already included a polarization curve class and so user-control over curves was easily added. Curve data was supplied within the CPBEM input data file and curve selection controls were added to anode and damage area dialogs. These controls permit selection of a polarization curve, but not modification of curve data. Modification of curve data must be done by manual editing of the input file, prior to loading it into CPBEM.

4.5 Line-of-form Interpolation

As previously stated, the driver program passes clipped lines-of-form to the Fortran program for meshing. One consequence of this approach was that the generated mesh would extend back only as far as the last wetted line-of-form. If the specified waterline was even slightly below the bottom of the aft-most line-of-form, the mesh would extend only as far as the penultimate line, even though the wetted hull extended further aft.

This problem was addressed by creating an algorithm that generates an extra line-of-form at the longitudinal location where the waterline intersects the hull center-line, as shown in figure 4.5. After determining the wetted portion of the two lines adjacent to this location, the new line was generated by way of simple linear interpolation. This new line would then be added to the list of lines past to the Fortran program.

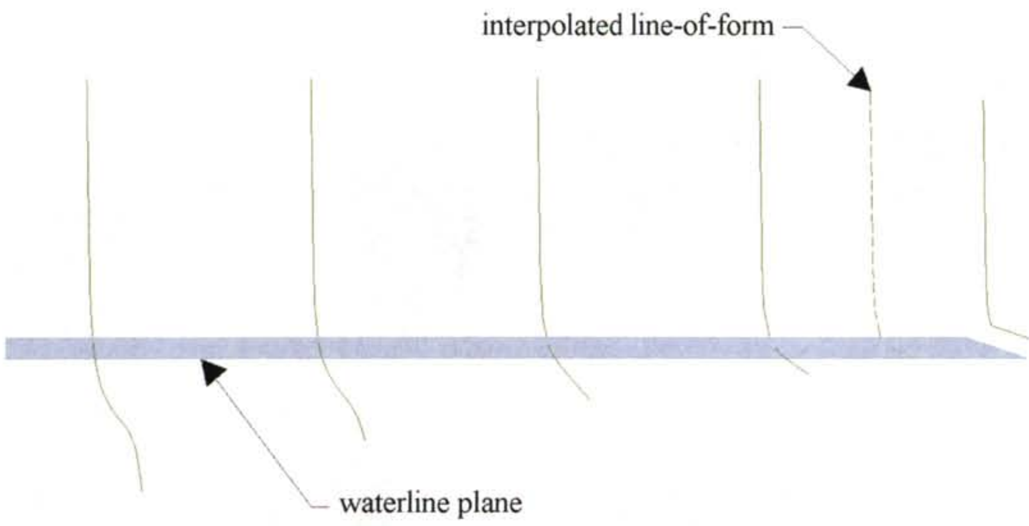

Figure 4.5 Interpolated Line-of-form

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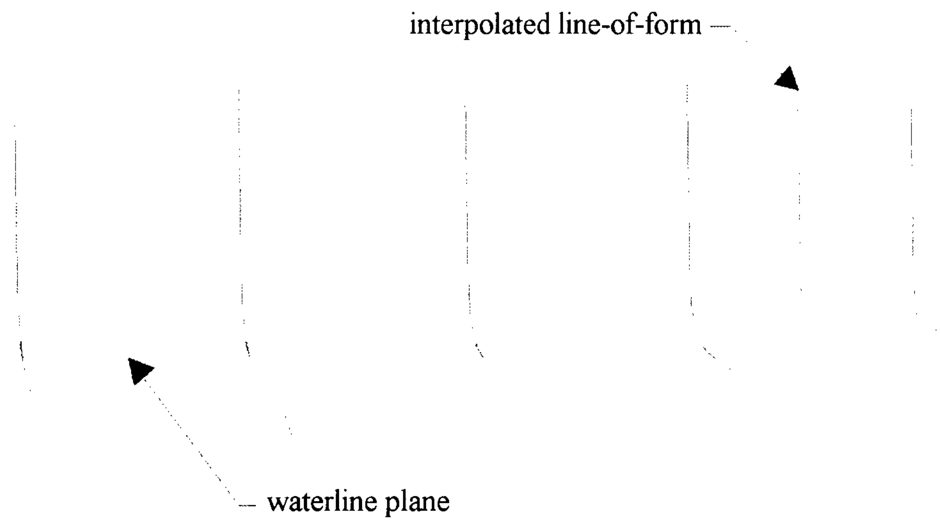

Figure 4.5 Interpolated Line-of-form

5. SOLVER CONTROLS

In this chapter, a description of the latest modifications made to the CPBEM solver will be presented. These modifications include upgrades to the iterative solver algorithm, provision of an option for modelling multiple cathodic and anodic regions using one or more polarization curves, and provision of a capability for computing the electric potentials and electrostatic fields at user specified locations in the fluid. A complete discussion of this work is provided in the sections below

5.1 Multiple Polarization Curves

In previous versions of the CPBEM solver, a single set of cathodic and anodic polarization curves were used to represent the electro-galvanic behavior of the entire ship structure. In order to provide users with the capability to model multiple damage areas, however, the CPBEM solver required upgrading in order to support the definition of a series of cathodic and anodic polarization curves.

After studying the existing format of the CPBEM solver, it was determined that providing individual boundary element panels with a reference to a polarization-resistance curve would satisfy the modeling requirements of the user while preserving the overall structure of the original code.

5.2 Modifications to the Iterative Solver

The iterative solution technique developed for use in the current CPBEM code is based on the Successive Overrelaxation Method, or SOR. Generally speaking, the SOR is essentially an extrapolation of the Gauss-Seidel method. This extrapolation takes the form of a weighted average between the previous iterate and the computed Gauss-Seidel iterate successively for each unknown value of the surface electrical potential, i.e.:

$$x_i^{(k)} = \omega \bar{x}_i^{(k)} + (1-\omega) x_i^{(k-1)} \tag{5.1}$$

where $\bar{x}$ represents the Gauss-Seidel iterate, ω represents the extrapolation factor or relaxation parameter, and k represents the iteration number.

5.2.1 Choosing the Value of the Extrapolation Factor

If ω equals one, the SOR method reduces to the Gauss-Seidel method. It is also important for users to note that Kahan[1] has shown that the SOR fails to converge if ω is outside the interval (0,2). Though technically the term underrelaxation should be used when $0 < \omega < 1$, for convenience the term overrelaxation is now used for any value of $\omega \in (0,2)$.

In general, it is not possible to compute in advance the value of ω that is optimal with respect to the rate of convergence of SOR. Even when it is possible to compute the optimal value for ω, the expense of such computation is usually prohibitive. As a result, the CPBEM solver has been modified to allow for user definition of relaxation parameter (see Figure 5.1).

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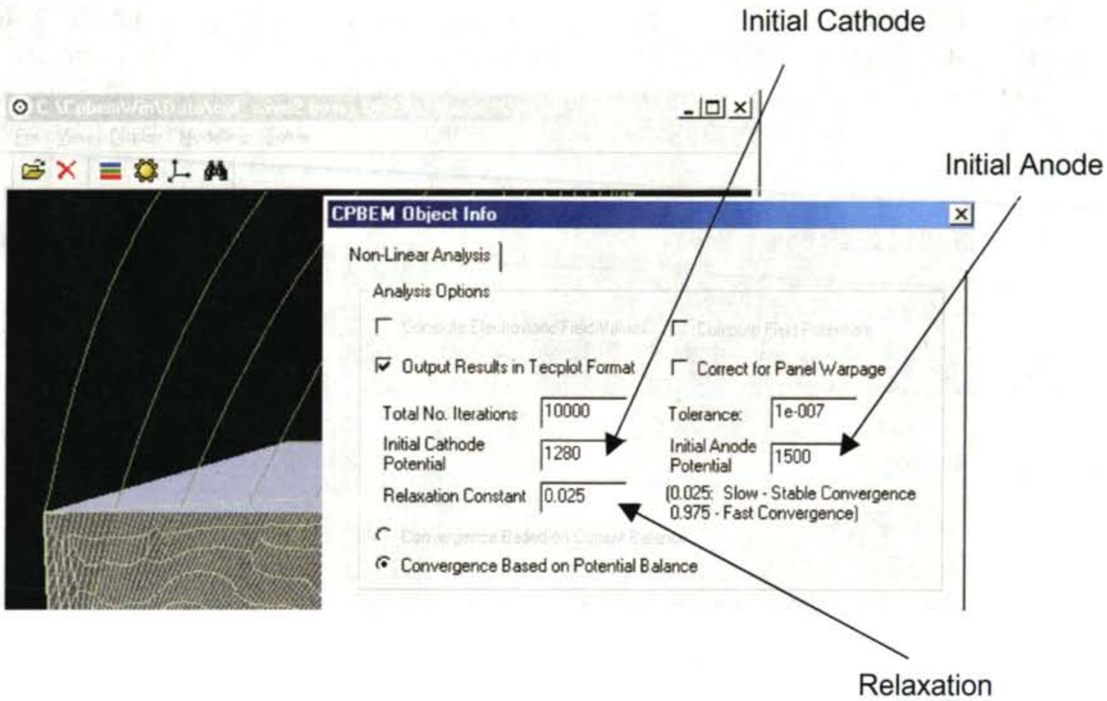

Figure 5.1: User Definition of Relaxation Parameter

5.2.2 Definition of Initial Conditions

In addition to the modifications described above, the CPBEM code was also upgraded to allow for user definition of the initial cathodic and anodic potentials used by the iterative solver (see Figure 5.1). By allowing the user to enter these values, which may be based on experimental data or engineering judgement, the number of iterations required in order to achieve convergence (and hence overall run times) can be reduced.

5.3 Computing the Electrostatic Field

Computing the electrostatic field generated by either galvanic or ICCP ship board systems requires the solution of the following expression,

$$\vec{u} = \sigma \nabla \phi \tag{5.2}$$

where $\bar{i}$ represents the current density vector, σ represents the conductivity of the electrolyte (sea water), and ϕ represents the electrical potential. Providing this capability within the existing CPBEM code required two significant upgrades to the solver: first, the ability to compute electrical potentials at arbitrary locations within the electrolyte, and second, the capability to compute the gradients of these field potentials.

5.3.1 Computing Field Potentials

Computation of field potentials can be viewed as a post-processing step. Following the solution of the wet surface potentials and current densities, the field potentials can be computed using the following boundary integral equation [2],

$$\phi(p)=\frac{1}{4\pi}\int_{\Omega}\left\{\phi(q)\frac{\partial G(p,q)}{\partial n_q}-G(p,q)\frac{\partial \phi(q)}{\partial n_q}\right\}dS_q \tag{5.3}$$

where $\phi(p)$ represents the electrical potential at a point inside the electrolyte (but not on the wet surface), Ω represents the wet surface of the ship structure (that portion of the ship surface exposed to the electrolyte), $\phi(q)$ represents the electrical potential at a point q on the wet surface, $G(p,q)$ represents the Green's function, and n_q represents the outward normal of the wet surface (pointing into the electrolyte) at point q on the body surface.

5.3.2 Computing the Gradients of Field Potentials

The computation of the gradients of the field potentials required the setup and solution of the following integral equation,

$$\nabla_p\phi(p)=\nabla_p\left(\frac{1}{4\pi}\int_{\Omega}\left\{\phi(q)\frac{\partial G(p,q)}{\partial n_q}-G(p,q)\frac{\partial \phi(q)}{\partial n_q}\right\}dS_q\right) \tag{5.4}$$

which reduces to the following form,

$$\nabla_p\phi(p)=\vec{i}E_x+\vec{j}E_y+\vec{k}E_z \tag{5.5}$$

where

$$E_x=\iint_{\Omega}\left(\left(\frac{n_{x_q}}{r_{pq}^3}-\frac{3(x_p-x_q)(x_p-x_q)n_{x_q}}{r_{pq}^5}-\frac{3(x_p-x_q)(y_p-y_q)n_{x_q}}{r_{pq}^5}-\frac{3(x_p-x_q)(z_p-z_q)n_{x_q}}{r_{pq}^5}\right)\phi(q)-\frac{(x_p-x_q)}{r_{pq}^3}\frac{\partial\phi(q)}{\partial n_q}\right)dS_q$$

$$E_y=\iint_{\Omega}\left(\left(\frac{n_{y_q}}{r_{pq}^3}-\frac{3(y_p-y_q)(x_p-x_q)n_{x_q}}{r_{pq}^5}-\frac{3(y_p-y_q)(y_p-y_q)n_{x_q}}{r_{pq}^5}-\frac{3(y_p-y_q)(z_p-z_q)n_{x_q}}{r_{pq}^5}\right)\phi(q)-\frac{(y_p-y_q)}{r_{pq}^3}\frac{\partial\phi(q)}{\partial n_q}\right)dS_q$$

$$E_z = \iint_{\Omega} \left(\left(\frac{n_{x_q}}{r_{pq}^3} - \frac{3(z_p - z_q)(x_p - x_q) n_{x_q}}{r_{pq}^5} - \frac{3(z_p - z_q)(y_p - y_q) n_{x_q}}{r_{pq}^5} - \frac{3(z_p - z_q)(z_p - z_q) n_{x_q}}{r_{pq}^5} \right) \phi(q) - \frac{(z_p - z_q)}{r_{pq}^3} \frac{\partial \phi(q)}{\partial n_q} \right) dS_q$$

where r_{pq} represents the distance between the field points $p(x_p, y_p, z_p)$ and $q(x_q, y_q, z_q)$.

Substitution of these expressions into Equation (5.3) yields the final form of the electrostatic field equation coded into the CPBEM solver,

$$\vec{u} = \sigma \nabla \phi = \sigma \left(\vec{i} E_x + \vec{j} E_y + \vec{k} E_z \right) \tag{5.6}$$

5.3.3 GUI support for Specifying Field Point Locations

In order to provide CPBEM users with a convenient means for defining the field locations at which the electric field is to be computed, a new "field point definition" dialog was added to the CPBEM GUI. This dialog box (see Figures 5.2 - 5.4) allows users to specify a grid-work

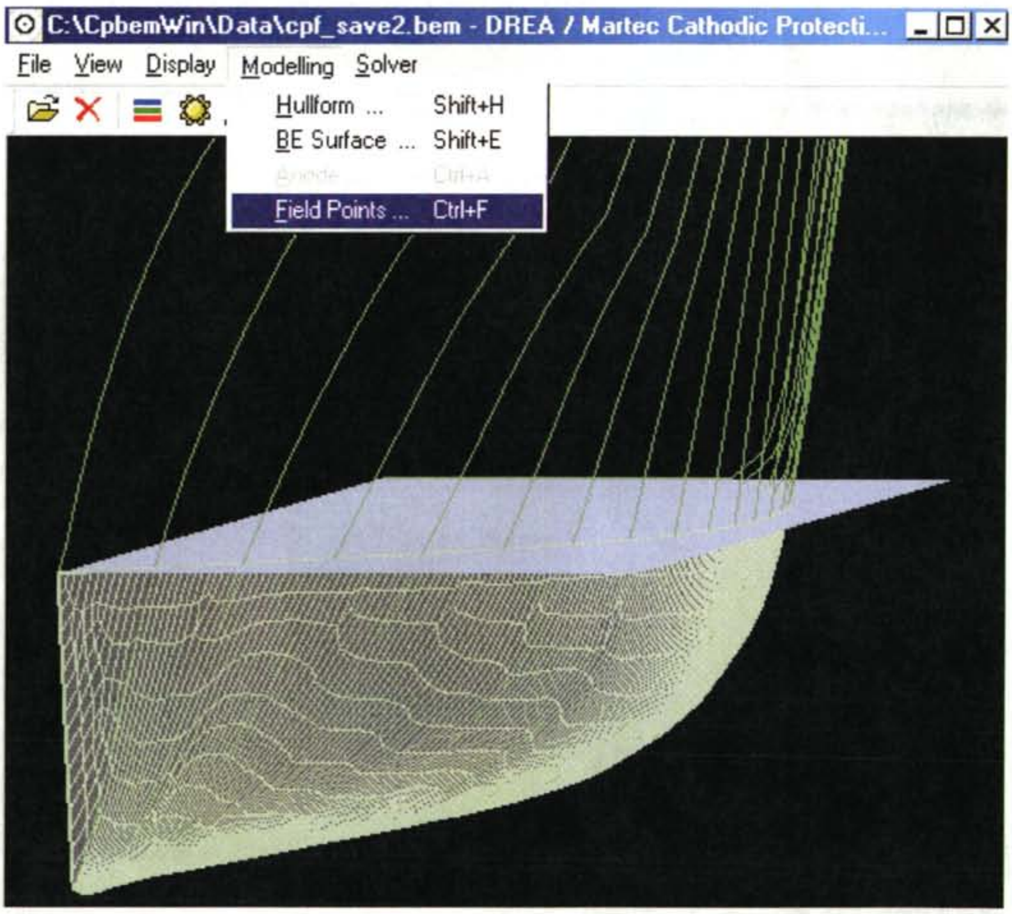

Figure 5.2: Field Point Modelling

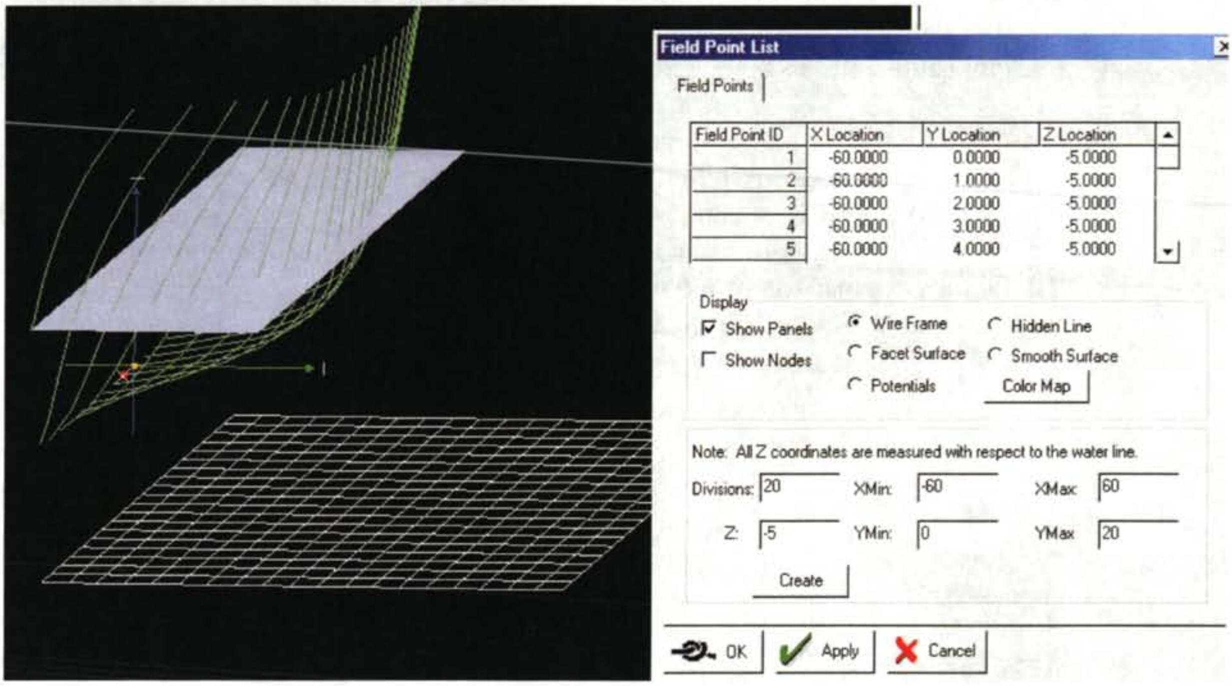

Figure 5.3: User Definition of Field Points

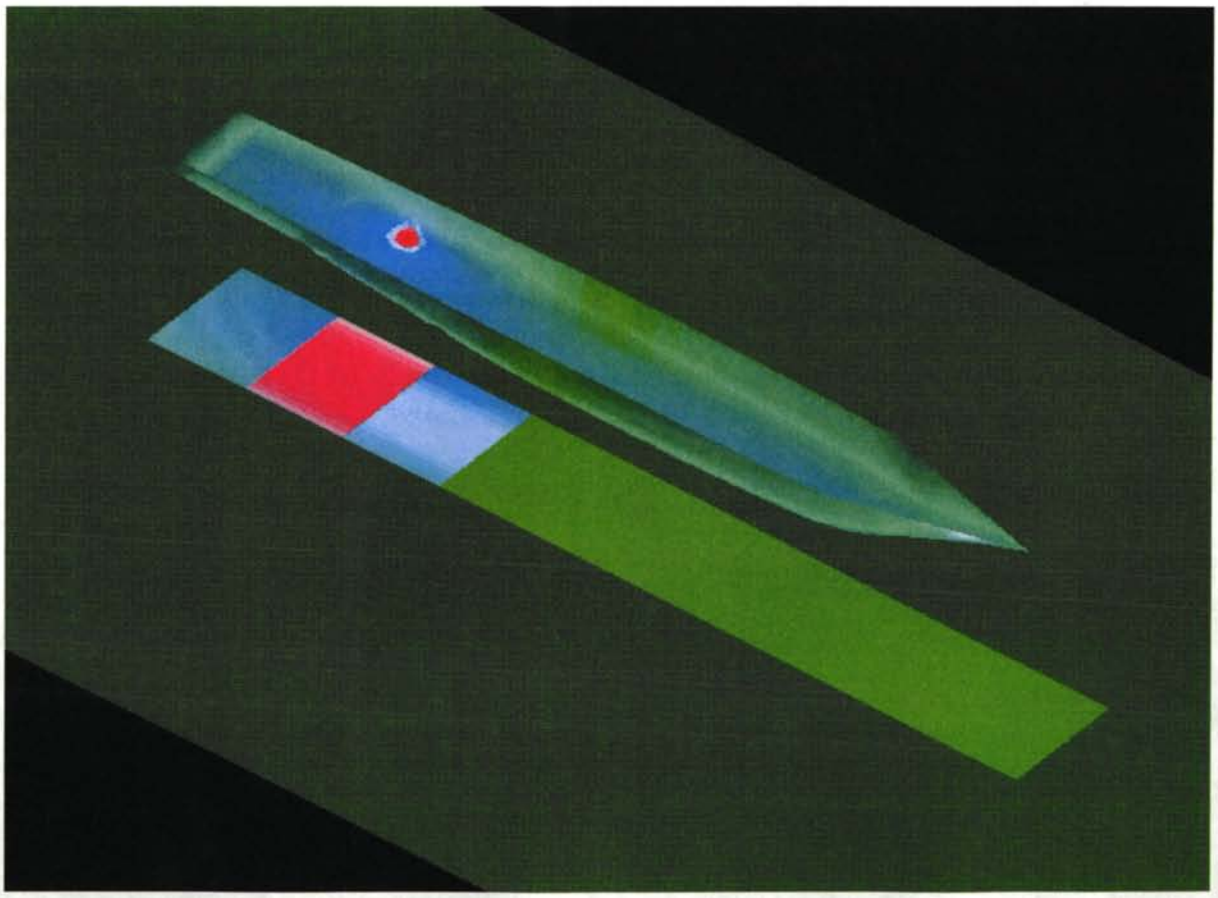

Figure 5.4: Field Potential Results Post-Processing

of points to be used as field points for electrostatic field calculations.

5.3.4 Comparison to BEASY Results

In order to evaluate the accuracy of the CPBEM electrostatic field processing capability, a simple model of a floating box-like structure was generated using both CPBEM and the commercial code BEASY[3]. A comparison of the field potential results is provided below in Figure 5.5 (these field potentials are with respect to the so-called far field potential as defined in Ref [2]), while a comparison of the electrostatic field is provided below in Figures 5.6-5.8. A review of these results shows excellent agreement between the two codes.

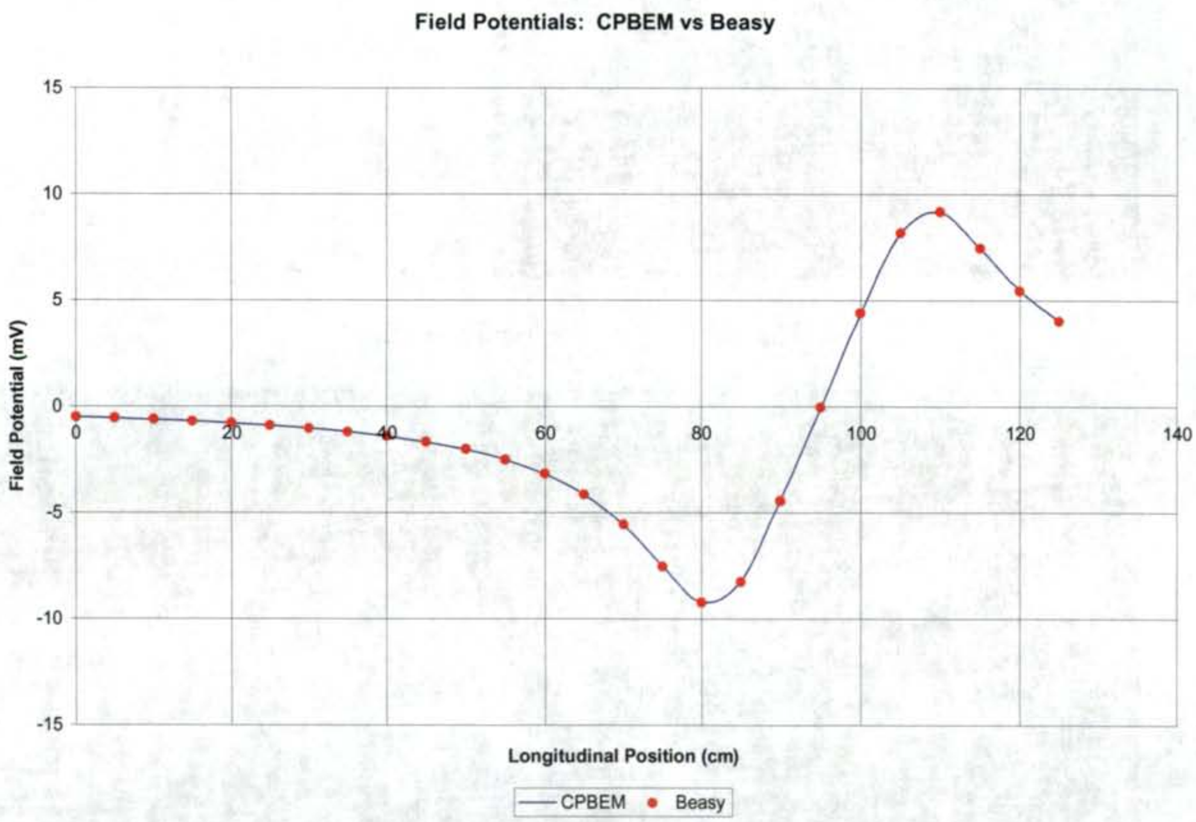

Figure 5.5: Comparison of CPBEM/BEASY Field Potentials

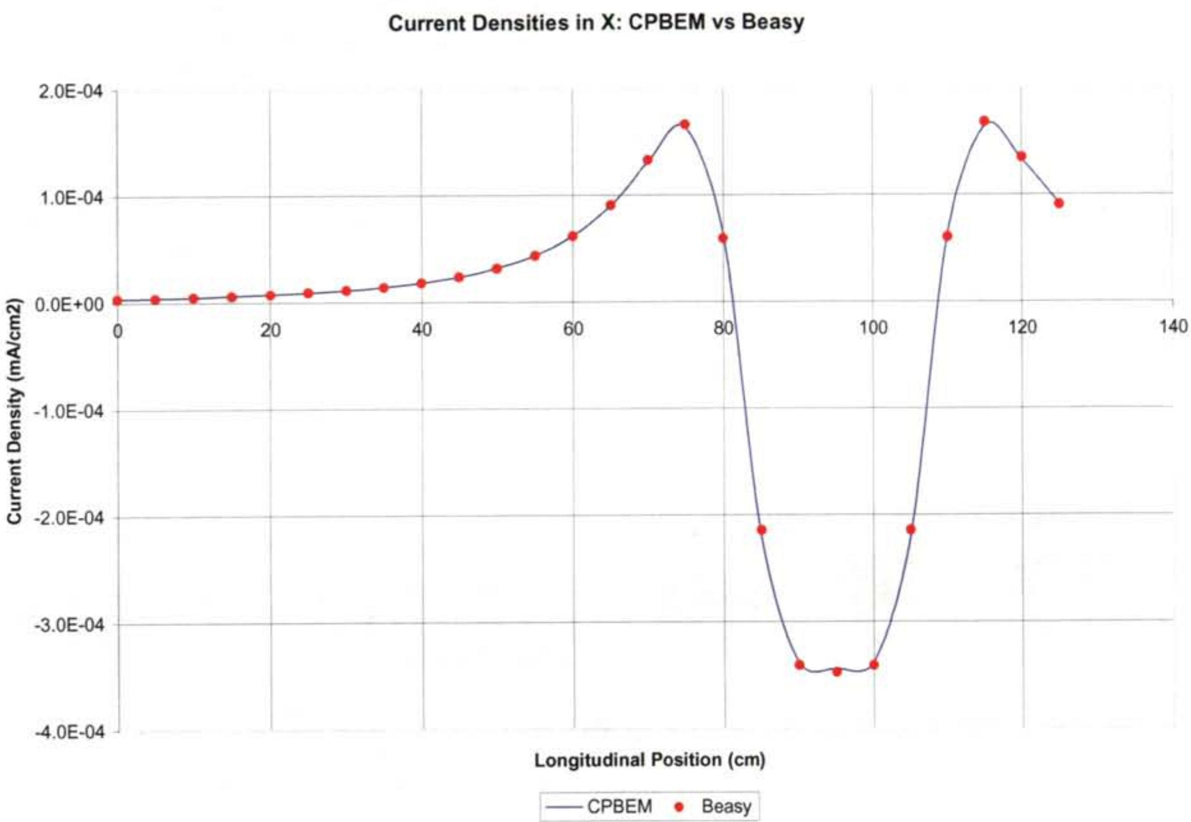

Figure 5.6: Comparison of CPBEM/BEASY X Current Densities

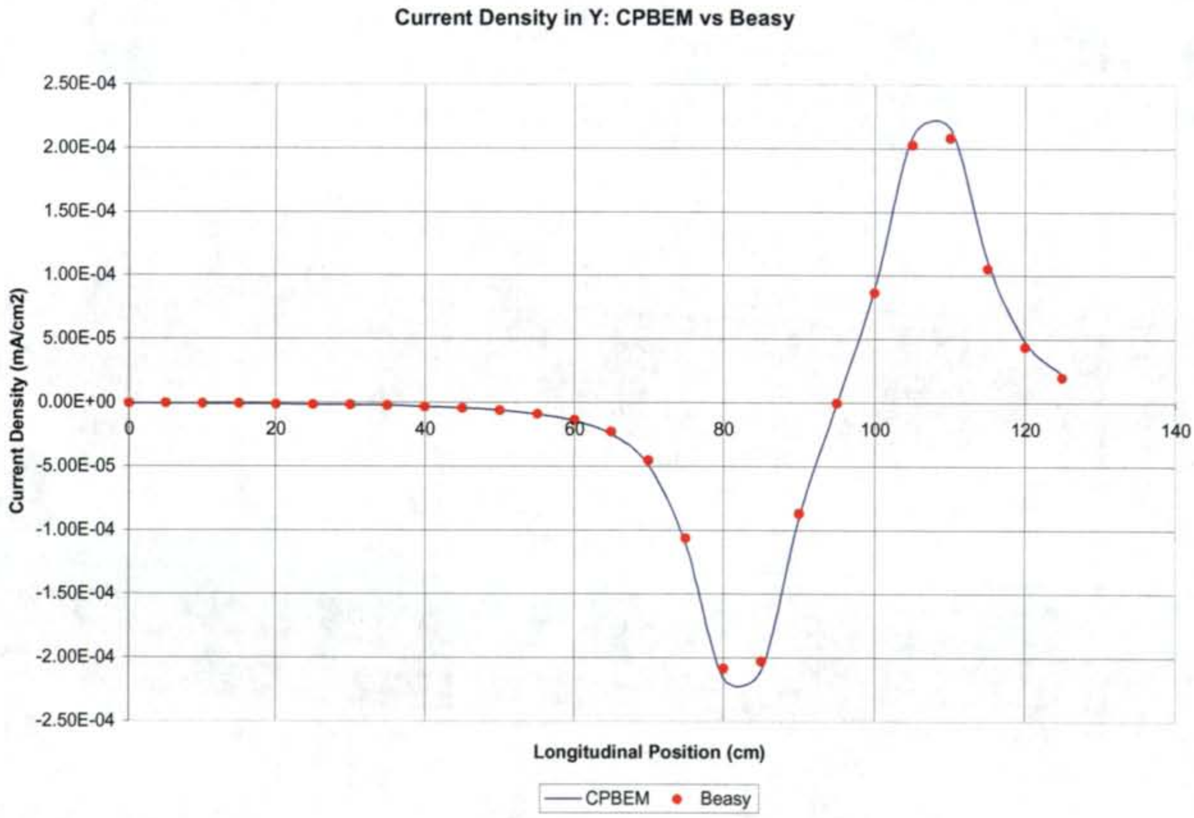

Figure 5.7: Comparison of CPBEM/BEASY Y Current Densities

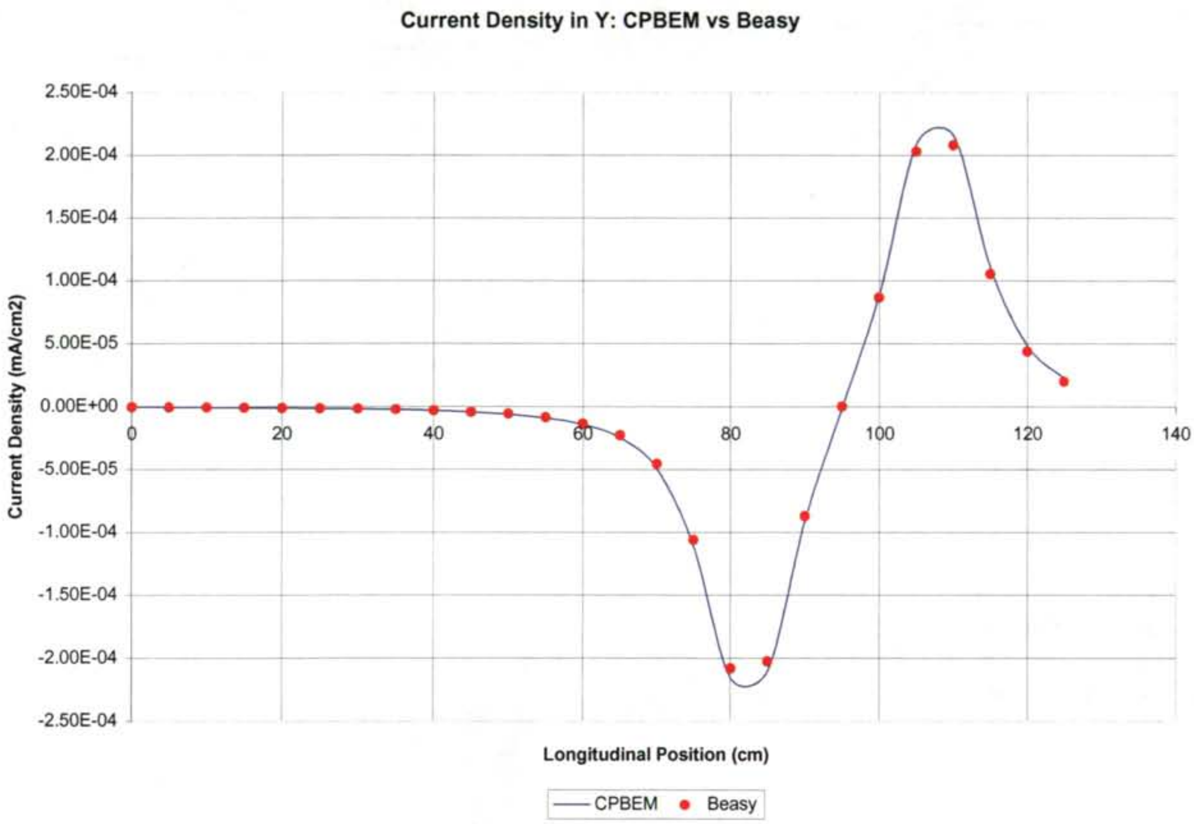

Figure 5.8: Comparison of CPBEM/BEASY Z Current Densities

6. POSTPROCESSOR

In order to provide the users of the CPBEM code with a means to graphically assess the results of the numerical simulations, CPBEM was upgraded to allow for the display of color contour plots of both surface electric potential and field potential values (See Figure 5.4). In addition, a CPBEM-to-Tecplot translator was also developed. The translator allows users to process CPBEM panel potentials and current densities using Tecplot's advanced post-processing capabilities.

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2. J.M. Chung, "Numerical Solution of Nonlinear Boundary Value Problem Arising in Corrosion and Electroplating Modeling with Applications to 3-D Ships and Marine Structures", PhD Thesis, Technical University of Nova Scotia, 1986.

3. BEASY Users Guide, Version 8.0, Computational Mechanics BEASY, Southampton, UK, 2001.

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In recognition of the significance of corrosion in its various manifestations to the life-cycle costs of naval ships, the Dockyard Laboratory of Defence Research Establishment Atlantic has embarked upon a multiphase study related to the development of boundary element analysis methods to support cathodic protection system studies. CPBEM, a PC based software suite that models both sacrificial and impressed current cathodic protection systems for surface ships, was developed. Several enhancements were made to CPBEM in current work to address several shortcomings identified during the recent application of CPBEM to modern frigates. Enhancements were made to the graphical user interface making it compliant with the Windows style of user interaction. Modelling capabilities were extended, through the use of a new improved meshing algorithm based on the quadrilateral paving methodology, to include an ability to describe anodes in close proximity to one another, and to describe the transom stern of the ship. Provisions for multiple polarization curves and paint damage areas were made. Other enhancements included the ability to compute the electric potentials and electrostatic fields at user specified locations in the fluid. A Tecplot interface was also supplied.

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